UCRL-CONF-221911

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Analytic Expressions for Minimizing Hohlraum Wall Losses

M. D. Rosen

June 9, 2006

29th European Conference on Laser Interaction with Matter
Madrid, Spain
June 11, 2006 through June 16, 2006

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Analytic Expressions for Minimizing Hohlraum Wall Losses

Mordecai D. ("Mordy") Rosen

Lawrence Livermore National Laboratory (LLNL), Livermore, CA, 94551

ABSTRACT

We apply our recent analytic solutions to the radiation diffusion equation to problems of interest for ICF hohlraums. The solutions provide quantitative values for absorbed energy, which are of use for generating a desired radiation temperature vs. time within the hohlraum. In particular we use analytic fits to the Rosseland mean opacity and to the specific heat of combinations of materials ("cocktails") designed to maximize the former while minimizing the latter. By doing so we find good agreement with numerical simulations and with experimental results. In particular we find that the wall loss savings of cocktails vs. the standard gold walled hohlraums have both pulse-length and temperature dependencies. Due to those dependencies we predict that NIF cocktail hohlraums will perform better than present day cocktail experiments. In addition, we apply our solutions to finding that density of foam hohlraum walls which minimizes wall loss by being of sufficiently low density to be supersonic, thus reducing kinetic energy losses, yet high enough density to not unduly suffer from enhanced specific heat capacity.

1. Introduction

On the Nova Laser at LLNL, we demonstrated (Rosen et al. 1994) many of the key elements required for assuring that the next laser, the 1.8 MJ National Ignition Facility (NIF) will drive an Inertial Confinement Fusion (ICF) target to ignition. The indirect drive approach converts laser light to x-rays inside a gold cylinder, which then acts as an x-ray hohlraum to drive the fusion capsule in its center. On Nova we've demonstrated good understanding of the temperatures reached in hohlraums and of the ways to control the uniformity with which the x-rays drive the spherical fusion capsules. In is paper we apply our recent analytic solutions to the radiation diffusion equation (Hammer & Rosen ("HR"), 2003) to recent problems of interest for ICF hohlraums. In particular we would like to operate NIF far from its damage thresholds, which forces us to find ways to make a hohlraum more efficient, such that it would require only 1 MJ of laser energy to provide the same drive to the ignition capsule that previously depended on nearly 2 MJ into a conventional gold hohlraum. In Section 2 we make general remarks on hohlraum energetics. In Section 3 we show how "cocktails" – mixtures of materials (not just pure Au) designed to maximize opacity and minimize specific heat - can be one approach to minimizing hohlraum wall losses and thus lower the laser energy input requirements that can achieve the same hohlraum temperature. In Section 4 we address other energy saving schemes, such as using low density walls. In Section 5 we briefly summarize our findings.

2. Hohlraum Energetics

We consider a hohlraum illuminated by a laser of energy E_L. It enters the hohlraum (usually made of a high Z material such as Au) and is absorbed along the inner walls where it is aimed. The hot plasma that ensues is a copious source of x-rays. We parameterize this process by a conversion efficiency η_{CE}. Thus we assume that $\eta_{CE}E_L$ worth of x-rays now flood the hohlraum and uniformly bath the wall areas of all that they see. Some of the x-rays are absorbed by the capsule, and some leave the hohlraum through the laser entrance holes (LEH). Since the capsule ablator is normally of low Z material that does not re-radiate much, it, like the LEH, absorbs all the flux σT^4 that impinges on it. Thus these two energy loss channels are σT^4 times the area of the capsule and LEH respectively, integrated over time. Our major challenge is to calculate the energy absorbed by the high Z wall subject to the flux of x-rays. The time rate of change in internal energy (per unit volume) would be equal to the divergence of the diffusive flux. For our system there are 2 fields of energy to consider: matter and radiation. The energy density of matter we write as ρe_{th}, where e is the specific energy, and the radiative flux is $F = -(4/3)\lambda d\sigma T^4/dx$. Thus:

$$\frac{\partial}{\partial t}\left(\rho e_{th}\right) = \frac{\partial}{\partial x}\left(\frac{4\lambda_R}{3}\frac{\partial}{\partial x}\left(\sigma T^4\right)\right) \qquad (1)$$

Before proceeding with any formal solutions, we can see how far simple dimensional analysis can take us. We write down Eq. (1) dimensionally:

$$\frac{\rho e}{t} \sim \frac{1}{x}\lambda\frac{\sigma T^4}{x} \sim \frac{1}{x}\frac{1}{\kappa\rho}\frac{\sigma T^4}{x} \qquad (2)$$

where the opacity $\kappa = 1/\rho\lambda$. We recast this in terms of the "Marshak front areal density" m_F:

$$m_F^2 \equiv \left(\rho X_F\right)^2 \sim \frac{\sigma T^4 \bullet t}{\kappa \bullet e} \qquad (3)$$

A non-linear Marshak heat wave of radiation (Marshak 1958) progresses diffusively through the material. A flat-topped T(x) profile takes a sharp nose-dive to zero at a front position x_F. A $T(x)= T_0\ \{1 -[x/x_F(t)]\}^{1/4}$ profile is a good approximation to the solution. To complete this analysis we need to know the T,ρ dependencies of κ and e. For Au we find that

$$\kappa = \kappa_0\, \rho^{0.2} / T^{1.5} \quad \text{and} \quad e = e_0 T^{1.6} / \rho^{0.14} \qquad (4)$$

Eqs. (3) and (4) lead to:

$$m_F \sim \frac{T^{1.95} t^{1/2}}{\sqrt{\kappa_o \bullet e_o}\,\rho^{0.03}} \qquad (5)$$

Despite the tiny ρ dependence our task is not yet done. The energy (per unit area) in the wall is dimensionally em_F and e has some non-negligible density dependence, so we must find an expression for the density in terms of T and t. The heat front progresses very slowly through the solid density high Z material. An isothermal rarefaction wave progresses through the heated material, significantly decompressing it and inducing much hydrodynamic motion in this "blow-off" plasma. A way to proceed (Rosen (1979)) is to find an "average" density in this blow-off by reasoning that after some time t, an amount of mass (per unit area), $m_F(T,t,\rho)$, has been heated and expands into the vacuum at the sound speed $c_S(T,t,\rho)$, so simply set $\rho=m_F/c_S t$. This accomplishes what we sought- a way to relate ρ (implicitly) to T & t. But since all ρ dependencies of m_F and c_S are power laws it is straightforward to solve for ρ explicitly in terms of T & t, and then plug back in to solve for m_F and then for E/A. We get:

$$m_F \sim \frac{T^{1.91} t^{.52}}{\left(\kappa_0 e_0\right)^{0.48}} \Rightarrow \frac{E}{A} \sim em_F \sim \frac{e_0^{0.7}}{\kappa_o^{0.4}} T^{3.34} t^{.6} \qquad (6).$$

We must now determine the exact coefficients. The full set of hydrodynamic equations, in Lagrangian format (m, not x) is:

$$(mass)\frac{\partial V}{\partial t} = \frac{\partial u}{\partial m}, (momentum)\frac{\partial u}{\partial t} = -\frac{\partial P}{\partial m}, (energy)\frac{\partial e}{\partial t} + P\frac{\partial V}{\partial t} = \frac{4}{3}\frac{\partial}{\partial m}\frac{1}{\kappa}\frac{\partial \sigma T^4}{\partial m} \qquad (7)$$

Here V=1/r. We supplement these equations with equations of state (Eq. (4), along with P=re/V with r=0.25. In HR we solve (7) by means of a perturbation technique with a small parameter ε = 1.6/(4+1.5)=0.29 the numbers being the power law T dependencies of e, aT^4, & $1/\kappa$ respectively. We make a self-similar assumption $T=T_B t^k f(m/m_F(t))$. We find to zero order, a spatial profile $f=(1-(m/m_F(t))^{1/4}$ where $m_F(t) = m_{F0} t^{(1+4k)/2}$. The ρ and u profiles are, to the same order, those of an isothermal rarefaction. The first order solutions differ from all these by quantities of order ε. We verify energy conservation, integral E(x,t)dx = integral F(x=0,t)dt through order ε^2, where E includes internal and kinetic energy.

We quote here the results for 2 useful choices of k: 0 & 0.18. The scaling of m & E/A are precisely those of Eq. (7) as they must be. The coefficients are m_{F0} = (9.9,7.4) 10^{-4} g/cm^2 respectively, and E/A=(0.58,0.39) hJ/mm^2 respectively. The absorbed flux is given by $F=F_0T^{3.34}$ $t^{-0.41}$ with coefficients F_0=(0.34,0.46) hJ/ns/mm^2. Note that E/A is simply the time integral of F. Also be aware that for the k=0.18 case you must remember to put the time dependence of T = T_0 $t^{0.18}$ into all of these equations. Thus for example the E/A (for k=0.18) = 0.39 $T_0^{3.34}$ $t^{1.2}$ hJ/mm^2. We can now, predict the hohlraum temperature for a given hohlraum geometry and incident laser pulse. To calculate all of this analytically we adopt a simple "source=sink" model. The source is the laser energy E_L, converted to x-rays, so that now η_{CE} E_L worth of x-rays bathe the hohlraum walls. We set that source equal to the energy sinks, which for a very simple hohlraum (no capsule) is the wall loss (the E/A of the previous paragraph times the area of the walls), and the LEH loss which is the time integral of σT^4 times the area of the laser entrance holes. We use convenient "radiation hohlraum units" ("rhu") in which T is measured in hectovolts (hundreds of eV), area in mm^2, time in ns, mass in gm and energy (a bit clumsily) in hectojoules. With these units, σ = 1.03 and normalized irradiance is 10^{13} W/cm^2 (= hJ/mm^2 ns = 10^2 J /10^{-2} cm^2 10^{-9} s) and similarly, normalized power is 10^{11} W (= hJ/ns = 10^2 J /10^{-9} s).

As an example we take the following "scale 1" hohlraum illuminated on the Nova laser at LLNL in the 1990's. It was a gold cylinder of length L = 2.5 mm, and radius R = 0.8 mm, and on each end a disk sealed the cylinder. Each disk had a "50% LEH" namely a laser entrance hole of radius 0.4 mm. One immediately calculates the wall area A_W = 15.6 mm^2 and A_{LEH}=1 mm^2. The source energy, a "flat top" laser power of 100 – 300 hJ/ns for a duration of 1 ns. (= 10-30 TW). Our simulations predict a $\eta_{CE} = 0.7\ t_{ns}^{0.2}$. The efficiency increases with time in part because the albedo behind the conversion layer builds up with time. This time behavior helps explain an important experimental observation, that T rises as $t^{0.18}$, hence our interest as quoted above with the k=0.18 case. Equating η_{CE} E_L = η_{CE} $P_L t$ which scales as $t^{1.2}$ to the principal x-ray sink, the wall, E_W which scales as $T^{3.3}t^{0.6}$ (Eq. (6)) we see that these two terms will balance iff T = $T_0 t^{0.18}$. Conversely, if we wish to have a truly flat T = $T_0 t^0$, we need a $P_L(t)$ that "droops" in time. For the 30 TW experiment, the source of x-rays (at 1 ns) will be $0.7P_Lt$ =(0.7)(300)(1) =210 hJ. The wall loss E_W will be (using the k=0.18 HR result) 0.39 $T_0^{3.3}$ $t^{1.2}$ A_W = 0.39 $T_0^{3.3}$ (1) (15.6) = 6.24 $T_0^{3.3}$ at 1 ns. We must also calculate the LEH loss. The flux out the LEH will be $T^4 A_{LEH}$ so we integrate $t^{4(0.18)}$ in time and get E_{LEH}= 0.58 T^4 at 1 ns. Solving 210 = 6.24 $T_0^{3.3}$ + 0.58 T^4 results in a T=2.75 with 176 hJ of wall loss and 34 hJ of LEH loss (justifying our claim that most of the loss is in the walls). The resulting prediction of 275 eV matches data and simulations quite well. Repeating this calculation for say 10 TW (70 replaces 210) yields a T=1.99 again in agreement with data and simulation. Thus our simple model of source=sink with sinks calculated by HR organize the database very nicely.

3. Cocktails

When we consider Eq. (6) we see that in order to lower the E/A of a wall loss, we need to lower e and to raise k. Since e scales as Z/A the higher the A the lower (at a given T) will be the ionization state Z and hence e. Thus mixing in higher A elements into the wall will lower e. Moreover, if we do mix in a higher A element, at a given T, it will have different atomic levels and thus its opacity, if A is chosen properly, will be high at frequencies where Au's is low. Thus this "cocktail" of materials can accomplish both things. Experiments with cocktails (Orzechowski et al. 1996) compared the burn-through times t_{bt} of Au foils placed across a hole in the side of a 260 eV hohlraum, to those of AuGd cocktail foils. A delay in burn-through signal for the cocktail was seen. By Eq. (6) we expect (again for a k=0.18 case) that t_{bt} should scale as $mT_0^{-2}(e\kappa)^{1/2}$, so the higher κ of the AuGd cocktail caused the delay. Since then we have tried to measure the rise in T for a full cocktail (vs. Au) hohlraum at the same laser drive. The cocktail chosen was $U_{0.6}Dy_{0.2}Au_{0.2}$ which at NIF-like temperatures of 300 eV can save nearly 20% in wall loss. The baseline Au hohlraum at the Omega Laser at URLLE was a "scale 0.75" cylinder (L=2.06 mm, R=0.6 mm, with 66% LEH (R=0.4 mm) so that $A_W= A_{\text{end caps}} + A_{\text{cyl wall}} = 1.2 + 7.8 = 9.0\ \text{mm}^2$ and $A_{LEH} = 1\ \text{mm}^2$. The incident flattop power was 20 TW for 1ns. As above, we use the k=0.18 results of HR. We infer about an 8% reflectivity, so with a 68% conversion efficiency we get a source at 1 ns of 101 hJ. We set that equal to the wall loss $3.5T_0^{\ 3.3}$ and LEH loss $0.6T_0^{\ 4}$, solve for T and get T=2.55 with 76 hJ wall loss and 25 LEH loss. This 255 eV is very close to the data.

We fit our latest opacity/ EOS theory of Au as $\kappa = 6544\ \rho^{\ 0.18}/T^{\ 1.43}$ (cm^2/g) and $e = 3.33\ T^{\ 1.54}/\rho^{\ 0.15}$ (MJ/g), and of $U_{0.6}Dy_{\ 0.2}Au_{0.2}$ as $\kappa = 5670\ \rho^{\ 0.10}/T^{\ 0.90}$ (cm^2/g) and $e = 0.95\ e_{Au}$. The cocktail has a "flatter", less sensitive T, ρ behavior because it averages over several elements. We also note that the opacity of cocktails does not exceed that of Au until past 130 eV. Using that input, HR predicts for k=(0,0.18), for Au an E/A = (0.598,0.398) $T^{3.3}t^{0.6}$ (hJ/mm^2) respectively and for the $U_{0.6}Dy_{0.2}Au_{0.2}$ E/A = (0.604,0.407) $T^{3.1}t^{0.57}$ (hJ/mm^2) respectively. Thus, at 270 eV and 1 ns, the wall loss ratio (cocktail/Au) is (0.84,0.85) respectively while a full multi-group simulation gives (0.85,0.87), very close to HR theory but differing mostly because the opacity is hard to fit with a single power law. All of these were for T_B scaling as t^k. For U mixed with 6% Nb by weight (=14 atom %) add 1% to all those ratios.

Another outgrowth of these scaling laws is to notice that the wall loss ratio scales as $T^{-0.22}\ t^{\ -0.05}$ for k=0.18 and even for the "flat top " k=0 case the wall loss ratio has a $t^{\ -0.02}$ ratio. Thus to the degree that the Omega experiments are not either at the full NIF temperature of 300 eV, nor at the NIF pulse length of 3-4 ns, then the results from such experiments will be pessimistic in showing a wall loss ratio advantage of a cocktail hohlraum over Au than would a NIF ignition hohlraum. (The ratio for NIF is about 0.83). All of these time behaviors stem from the fact that early in time the lower T parts of the Marshak wave profile are relatively more important, and for low T the cocktail is actually worse than Au.

So let us redo the Omega hohlraum calculation for T with cocktail walls (actually shot with $U_{0.86}Nb_{0.14}$) and thus our E/A wall loss is $0.416\ T^{\ 3.1}$ at 1 ns vs. Au $0.39\ T^{\ 3.3}$. The solution now to $101 = 3.7\ T^{\ 3.1} + 0.6\ T^4$ is T=2.62 so we expect a 7 eV hotter hohlraum than the 255 eV Au hohlraum. Many shots were done with Au end plates and just a cylinder body of cocktail. Redoing that we must solve $101= 0.49T^{\ 3.3} + 3.2\ T^{\ 3.1} + 0.6T^4$ we get 2.61 thus we expect a 6 eV improvement for those type of cocktail hohlraums. However, until very recently there was only a

2.5 eV difference between Au and cocktail hohlraums. We believe that oxygen contaminated the cocktail walls in the process of making them. While Au does not bind to O, U & Dy certainly do. The trouble with O in the cocktail is that they are fully ionized so contribute about twice the Z per unit weight than the high Z elements, and thus raise e by raising the specific heat. Assuming the hohlraums were fully oxygenated we can redo our source=sink model once again but with a lossier wall loss due to the high e due to the oxygen. Now the E/A coefficient is 0.44 and, with Au end plates we solve $101 = 0.49\ T^{3.3} + 3.4\ T^{3.1} + 0.6\ T^{4}$ and get T = 2.575, a 2.5 eV difference from the 255 eV pure Au hohlraums, in rather close agreement with what was observed. The good news is that very recent shots in which great care has been taken to avoid oxygenation, has shown the cocktail hohlraums about 6 eV hotter than the Au ones, as expected.

4. Foam-walled Hohlraums and Other Energy Saving Schemes

Can we save on driver energy by making hohlraum walls out of low density high Z foams, which have less hydrodynamic motion (namely less radiation heated and ablated material that streams back into the hohlraum interior as a low density isothermal blow-off) and hence, reduced net absorbed energy by the walls? Using our HR analytic theory, as well as by numerical simulations (Rosen & Hammer 2005) we answered yes. We showed that low-density high Z foams can indeed lower wall loss by ~ 20% for a drive, T, that is flat in time. Remarkably, this reduction is universal- independent of the value of T or its pulse-duration t. We derived an analytic expression for the optimal density (for any given T and t) that will achieve this reduction factor and which agreed very well with numerical simulations. Reduced hydrodynamic motion of the wall material may also reduce symmetry swings, as found for heavy ion beam targets.

Full 2-D simulations also show that combining both these schemes works best, namely foam cocktail hohlraums. This idea has been tried in detail for a heavy ion reactor scale hohlraum (Callahan & Tabak 2000). It was optimized via tedious full 2-D simulations and a Au-Gd foam density of 0.1 gm/cc was arrived at. Applying its drive and pulse length, T = 2.5 and t=8, to our optimal density formula, we predicted 0.13 gm/cc, quite close to that value. We have also recently tested this foam concept using a cylinder of Ta_2O_5 made of either 4 gm/cc or 0.1 gm/cc, each with a gold ring hit by the laser that served as the x-ray source to drive the rest of the cylinder walls. They were performed by P. Young of LLNL at URLLE. A drooping pulse produced about a 100 eV flat-topped drive. The 0.1 gm/cc foams were (preliminary result) about 15% brighter in accord with 2-D simulations and in accord with the “source=sink” approach of this paper, when albedo effects are taken into account. More experiments are planned in a more fully enclosed hohlraum geometry. More work is needed to extend this idea to shaped pulses, for which perhaps graded density foams may be required.

Another “trick” to save energy is to emplace axial shields (small Au disks) to block the capsule’s view of the cold LEH (Amendt et al. 1996). The simulation "observables" were a 228 eV hohlraum with no shine shields vs. a 241 eV drive on capsule for one with shine shields. Why would a hohlraum that introduces about 500 J more wall loss via the shine shield disks, actually produce a hotter hohlraum rather than a cooler one? The answer (Rosen 1996) to the paradox is that we have created an inside out hohlraum, in which the central section is a “hot interior hohlraum”, and drives the capsule. Indeed, the outer sections of these hohlraums are “cold exterior hohlraums”, and are predicted by simulations to be only about 215 eV. We have also derived all of these values analytically (Rosen 1994b). This concept has been tested successfully. The drive increase in the hot interior hohlraum was measured via the decreased implosion time of a capsule therein. It was also noticed in those experiments that the axial shine shields provided yet another "knob" to control the symmetry of the illumination onto the capsule.

5. Summary

We have presented 3 ways to reduce wall losses, each by nearly 20%, and which can be used in conjunction with one another, leading to an overall energy savings of $(0.8)^3$ or about 0.5. This will allow NIF to operate quite far from its damage thresholds, and still provide the drive to the capsule in the center of the hohlraum required for ignition.

We gratefully acknowledge conversations with our colleagues: LLNL theory and design: J. Hammer, O. Jones, L. Suter, J. Edwards, A. Szoke, J. Castor, S. MacLaren, R. Thiessen, and P. Amendt; AWE: B. Thomas, P. Thompson, M. Stevenson and S. McAlpin; LLNL experimentalists: J. Schein, P. Young, E. Dewald, N. Landen, S. Glenzer, K. Campbell, R. Turner, R. Kauffman, C. Darrow, H. Kornblum, J. Porter, T. Orszechowski, and W. Hsing; Computational and data base: G. Zimmerman, J. Harte, D. Bailey, M. Marinak, J. Albritton, B. Goldstein, and B. Wilson; LLNL Target fabrication: R. Wallace, J. Gunther, J. Kass, and A. Hamza; GA: H. Wilkens, A. Nikroo, J. Kaae, T. Back, J. Kilkenny, and M. Campbell. Sandia: R. Olson, G. Rochau, and R. Leeper. The encouragement and support of B. MacGowan, B. Hammel, J. Lindl, E. Moses, G. Miller, C. Verdon, B. Goodwin, and M. Anastasio are also gratefully acknowledged. This work was performed under the auspices of the US. Department of Energy by UC, Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

6. References

Amendt, P., Murphy, T., & Hatchett, S. (1996). Novel symmetry tuning in Nova hohlraums using axial gold disks. *Physics of Plasmas* **3**, 4166-4171.

Callahan, D. and Tabak, M. (2000). Progress in target physics and design for heavy ion fusion. *Phys. Plasmas* **7**, 2083-2091.

Hammer, J. H. & Rosen, M. D. (2003). Exact solutions to the diffusive radiation transport equations. *Physics of Plasmas* **10**, 1829-1845.

Marshak, R. E. (1958). Effects of radiation on shock wave behavior. *Phys. Fluids* **1**, 24-29.

Orzechowski, T., Rosen, M., Kornblum, H., Porter, J., Suter, L., Thiessen, A., & Wallace R. (1996). The Rosseland mean opacity of a mixture of gold and gadolinium at high temperatures. *Phys. Rev. Lett.* **77,** 3545-3549.

Rosen, M. D. (1979). Scaling law for radiation temperature. Laser Program Annual Report (1979), Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50055-79, pp. 2-37 -46 (unpublished), extensively quoted / used in J. Lindl, Phys. Plasmas, **2**, 3933, (1995).

Rosen, M. D., Lindl, J. D., and Kilkenny, J. D. (1994a). Recent results on Nova. *Journal of Fusion. Energy* **13**, 155-166.

Rosen, M. D., (1994b). Scaling laws for non-conventional hohlraums, *Bulletin of the American Physical Society* **39**, 1684.

Rosen, M. D. (1996). The science applications of the high-energy density plasmas created on the Nova laser. *Phys. Plasmas* **3**, 1803-1812.

Rosen, M. D. and Hammer, J. H. (2005). Analytic expressions for optimal inertial-confinement-fusion hohlraum wall density and wall loss. *Phys. Rev E. 72, 056403-1-5.*